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Thesis

MASS-SPECTROGRAPHS IN THEORY AND PRACTICE

by

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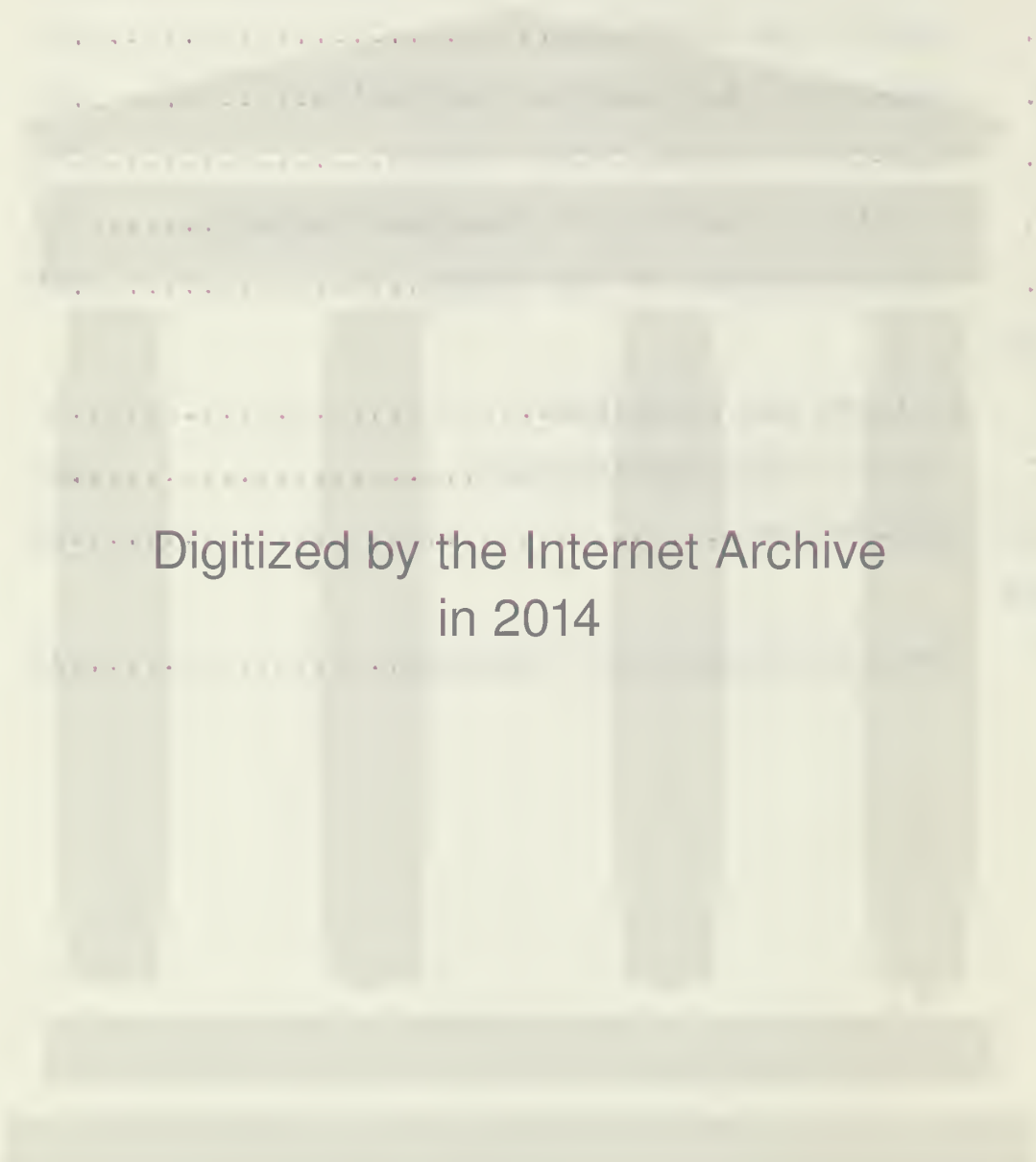
MASS-SPECTROGRAPHS IN THEORY AND PRACTICE

Topical Outline of Thesis

List of Figures, Plates, and Tables



Introduction

The following thesis, "Mass-Spectrographs in Theory and Practice," was undertaken by Charles S. Tarr while studying at Boston University for the degree of Master of Arts in Physics. The purpose of this thesis was to gather some of the more important facts in the field of mass-spectroscopy and to present them in a clear and concise manner under one cover.

Following this introduction is a description of several kinds of mass-spectrographs that have actually been built and whose utility has been proved by useful experiments. The principal discussion is confined to the mass-spectrograph of Aston. Francis William Aston invented a mass-spectrograph which is by far the most used of any of the kinds yet invented. The discussion of this instrument with diagrams, plates, and derivations of formulae forms the main body of the thesis. An interpretation of some of Aston's work is given, to a sufficient extent to enable the reader to understand mass-spectra plates, provided he has a basic knowledge of Physics.

Kinds of Mass-Spectrographs

Positive Rays and the Parabola Method of J.J. Thomson.

In 1886 Goldstein discovered positive rays in an electrical discharge at low pressure. In experiments with a perforated cathode he observed streamers of light behind the perforations. These he assumed to be due to some sort of rays traveling in the opposite direction to the cathode rays, and so passing through the apertures in the cathode. Wein subsequently showed that these rays could be deflected by a magnetic field. Sir J.J. Thomson fully investigated this phenomenon and called these rays "Positive Rays" because they usually bear a positive charge.

Positive rays are produced by ionization at low pressure in a strong electric field. Ionization, in the simplest case, is the detachment of one electron from a neutral atom which may be caused by collisions or radiation. The resulting fragments are charged equally and oppositely. The negative particle is the electron, and is the same whatever atom is ionized. It is very light and attains a high velocity in the electric field and thus becomes the cathode ray. The positive particle is characteristic of the atom ionized and is much heavier than the electron, about 1838 times the mass of the electron, and will therefore attain a much lower velocity under the action of the electric field. If, however, the field is strong and the pressure low so that it does not collide too frequently

with molecules of the gas present in the tube, it will attain a high velocity in the opposite direction and so becomes the "positive ray." Positive rays can be formed from either atoms or molecules and so any measurement of their masses will give direct information as to the masses of atoms of elements, and molecules of compounds. Chemical analysis gives a mass which is the mean of all the isotopes present in the atom or molecule whereas physical analysis gives the mass of each individual isotope separately.

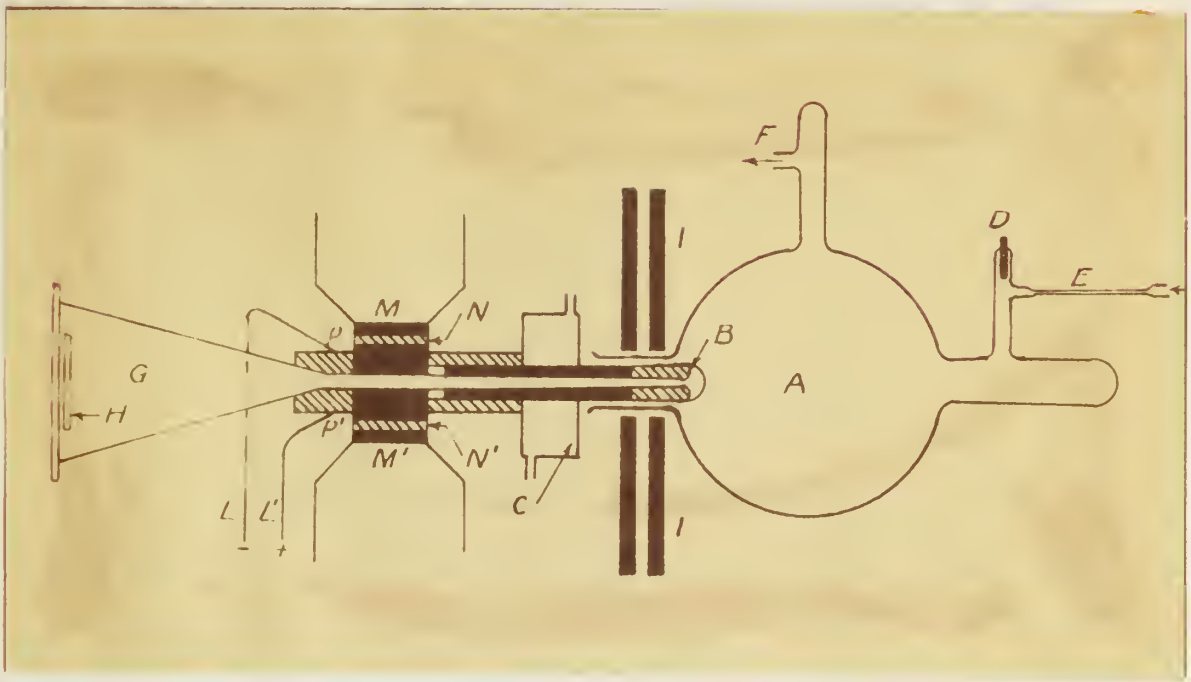


Fig. 1. Positive Ray Apparatus[1]

A Flask similar to X-ray bulb of about 1½ liters capacity.

B The cathode, with an aluminum face, hemispherical end, and funnel shaped opening. The rest of the cathode is a fine-bore tube, usually of brass, about 7 cms. long and may be as small as 1/10 m.m. diameter.

C Water cooling jacket for cathode.

D Aluminum anode.

E Capillary through which gas under investigation is admitted.

F Connection to pump to remove gas. The pressure is such that a discharge potential of 30,000 to 50,000 volts is necessary. The beam which finally passes through the tube is subjected to analysis.

1 F.W. Aston, "Isotopes" p. 28

P,P' Soft iron pole pieces, of

M,M' Powerful electro magnet, insulated from P,P' by

N,N' Sheets of mica.

L,L' Leads by which P,P' can be raised to any desired potential

G Highly exhausted camera

I,I' Shields to protect bulb from stray magnetic fields.

The apparatus used by Thomson in his parabola method of analysis consists essentially of allowing the rays to pass through a very narrow tube and then subjecting the emergent beam to electric and magnetic fields. In Fig. 1, is shown a diagramatic drawing of Thomson's Positive Ray Apparatus.

"If there is no field between the plates P,P' the beam of rays will strike the screen at a point in line with the fine tube called the undeflected spot. If an electric field of strength X is now applied between the plates a particle of mass m, charge e, moving with velocity v, will be deflected in the plane of the paper and will no longer strike the screen at the undeflected spot, but at a distance x from it. Simple dynamics show that if the angle of deflection is small, $x = k(Xe/mv^2)$. In the same way, if the electric field is removed and a magnetic field of strength H applied between P and P', the particle will be deflected at right angles to the plane of the paper and strike the screen at a distance y from the undeflected spot where, $y = k'(He/mv)$, k and k' being constants depending solely on the dimensions and form

of the apparatus used. If now, with the undeflected spot as origin, we take axes of co-ordinates OX, OY along the lines of electric and magnetic deflection, when both fields are applied simultaneously the particle will strike the screen at the point (x,y) where y/x is a measure of its velocity and y^2/x is a measure of e/m, its ratio of charge to mass.

"Now "e" can only exist as the electronic charge 4.800 times 10^{-10} C.G.S., or a simple multiple of it. Thus if we have a beam of positive rays of constant mass, but moving with velocities varying over a considerable range, y^2/x will be constant and the locus of their impact with the screen will be a parabola branch pp' Fig. 2. When the other rays having a larger mass m' but the same charge are introduced into the beam, they will appear as another parabola branch qq' having a smaller magnetic displacement. If any straight line p,q,n be drawn parallel to the magnetic axis OY cutting the two parabolas and the electric axis OX in p,q,n it will be seen at once that $m'/m = pn^2/qn^2$. That is to say, the masses of two or more particles can be compared directly by merely measuring lengths the ratio of which is entirely independent of the form of the apparatus and the experimental conditions."[1]

[1] F.W. Aston, "Isotopes" p. 29 to 30

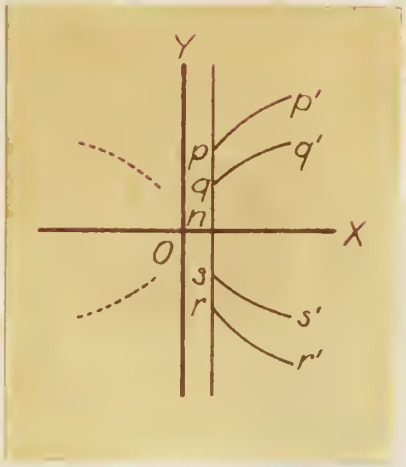


Fig. 2.
Positive Ray Parabolas.

In the photographic plate obtained (Plate I, page 8) at least one parabola must be one which comes from atoms or molecules of known mass. Then other parabolas can be measured and compared with this standard and their masses deduced as follows: Since OX (Fig. 2.) is an imaginary line and does not exist on the photograph the magnetic field must be reversed during the second half of the exposure thus giving two parabola branches rr' and ss' due to m and m' respectively. The masses are now in the ratio of pr^2/qs^2 or $m'/m = pr^2/qs^2$ [1] where p,q,r,s is any straight line cutting all the curves and is approximately parallel to the magnetic axis, OY. The measurement of these lengths is independent of any zero point and, if the curves are sharp, can be carried out fairly accurately.

[1] F.W. Aston "Isotopes" p. 30

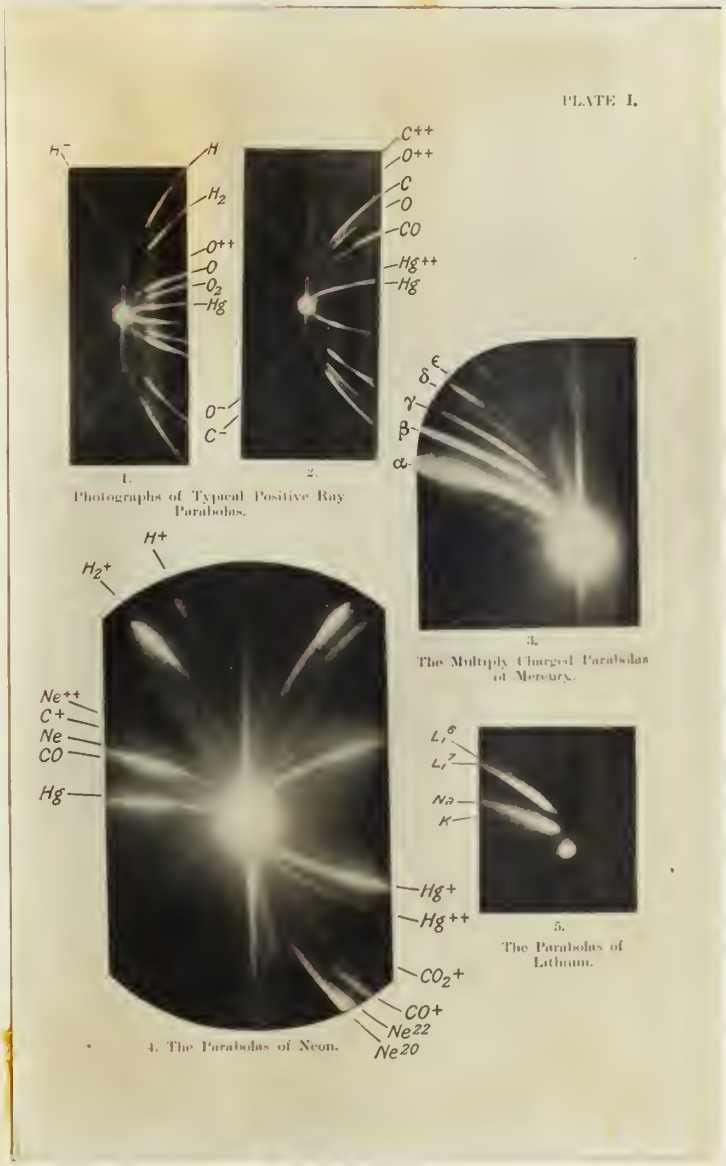


Plate I Positive Ray Parabolas (After Aston)

The Mass-Spectrograph of Aston

Francis William Aston, while working in the Cavendish Labratory, devised an instrument in which particles of the same mass would affect a photographic plate in the same place. This instrument was given the name of "Mass-Spectrograph" and a copy of a photograph of the original mass-spectrograph, as set up in the Cavendish Labratory in 1919, occurs on page 10, Plate II.

It is this type of mass-spectrograph which is the most common today and with which many valuable experiments have been made. These experiments were performed chiefly by Aston and deal with the isotopic constitution of the atoms of many elements.

Since Aston's Mass-Spectrograph is so well known and so widely used, the discussion following will be confined solely to this instrument.

The principle on which the mass-spectrograph operates is briefly as follows:--Rays, after arriving at the cathode face, pass through two very special slits and the resulting ribbon of rays is spread by passing through two parallel plates charged electrically. A diaphragm shields all but the central portion of rays and these are allowed to pass through a magnetic field which is at right angles to the electric field which is at right angles to the magnetic field. The resulting spectrum is photographed on an inclined plate.

Photograph of the Original Mass-Spectrograph set up in the Cavendish Laboratory in 1919.

B, Discharge Tube. *A*, Anode connected to high potential terminal of induction coil below table. *C*, Reservoir containing gas to be analysed. I_1, I_2, Charcoal-liquid air tubes exhausting slit-system and camera. *S*, Soft iron plates to shield discharge from stray magnetic field. *L*, Leads from high tension battery to electric plates. *M*, Du Bois electromagnet. *T*, Pea lamp for photographing fiducial spot. *V*, Vacuum-tight and light-tight control for moving photographic plate. *W*, Camera showing light-tight cap on the left. *H*, Magnet circuit ammeter. *O*, Magnet circuit control resistances. *G*, Gaede rotating mercury pump connected to the camera and the discharge tube by glass tubes and stopcocks.

Plate II Original Mass-Spectrograph (After Aston)

Mathematical Derivation[1]

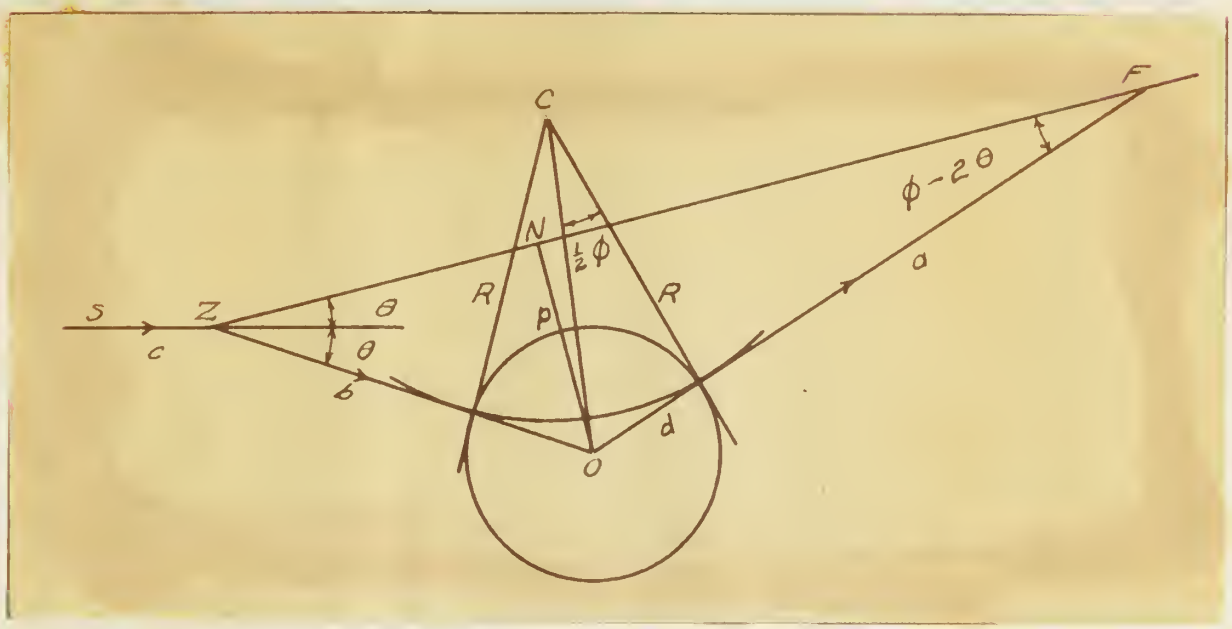


Fig. 3 Diagram for Mathematical Derivation

"In Fig. 3, let O be the center of the magnetic field, assumed uniform and circular, of radius d. Let Z be the virtual focus from which the rays diverge after passing the electric field, and F their focus on the plate which lies along ZF. Let R be the radius of the circular path, (center C) of rays of mass m in the magnetic field, and let p be the length of ON, the perpendicular from O to ZF. The angle Φ is the angle at C and FZO = 2 Θ. The angles Θ and Φ are the angles through which the rays are bent by the electric and

[1] Exact derivation taken from "Some Problems of the Mass-Spectrograph", by F.W. Aston and R.H. Fowler. Phil. Mag. V43 514-528 (1922)

magnetic fields respectively. Then:

$$\tan. \tfrac{1}{2}\Phi = \frac{d}{R},$$

and we know that, as the energy is constant, R varies as the m. We may therefore write

$$\tan. \tfrac{1}{2}\Phi = m_o/m,$$

where m_o (a constant) can be interpreted as that mass which under the conditions of the experiment is bent through one right angle in the magnetic field. It is only through m_o that the actual values of the fields affect the mass-scale on the plate.

"It appears from Fig. 3, that

$$NF = p \cot(\Phi - 2\Theta) = p\frac{1 + \tan\Phi \tan 2\Theta}{\tan\Phi - \tan 2\Theta}$$

but $$\tan\Phi = \frac{2\tan\frac{1}{2}\Phi}{1-\tan^2\frac{1}{2}\Phi} = \frac{2mm_o}{m - m_o}$$

by (1) hence $$\frac{NF}{p} = \frac{m - m_o - 2mm_o(\tan 2\Theta)}{2mm_o - (m - m_o)\tan 2\Theta} \qquad (2)$$

"N is, of course, a fixed point, which in the actual apparatus is approximately 5.4 cms. behind the fiducial spot. When m_o and the geometrical constants p and Θ are known, equation (2) enables us to calculate the position of the image on the plate for any desired mass.

The Linearity of the Mass-Scale

"It was observed that in most important part of the plate the mass scale was nearly linear--more precisely that NF was proportional to m over a wide range. Equation (2) enables us to explain this, and, in fact, to prove that

such linearity must always occur near $\Phi = 4\Theta$, which agrees exactly with experience. For if we write $(m/m_o)^{\frac{1}{2}} = Z$ we have:

$$\frac{NF/p}{m/m_o} = \frac{Z^2 - 1 + 2Z \tan 2\Theta}{Z^2(Z^2 - (Z^2 - 1) \tan 2\Theta}$$

An approximately linear scale of the observed nature will occur where:

$$\frac{d(NF/p)}{dm(m/m_o)} = 0 \quad \text{i.e.} \quad \frac{d}{dZ}\frac{(NF/p)}{(m/m_o)} = 0.$$

On differentiation and simplification we find that:

$$\frac{d(NF/p)}{dZ(m/m_o)} = \frac{2 (Z \tan 2\Theta - 1) ((3Z^2-1) \tan 2\Theta + Z(Z^2 - 3))}{Z^3 (2Z - (Z^2 - 1) \tan 2\Theta)^"}$$

Which vanishes when $1/Z = \tan 2\Theta$

i.e. when $\tan \frac{1}{2}\Phi = 2 \tan \Theta/$

Thus the mass-scale will be approsimately linear near $\Phi = 4\Theta$.

"Actual numerical calculation by (2) shows that the approximation to linearity should be (as was observed) very close. For the actual apparatus:

$$\Theta = 1/12 \text{ radian}, \quad \tan 2\Theta = 0.168.$$

Values of $\frac{NF/p}{m/m_o}$ in arbitrary units are given in the following table:

m/m_o	$\frac{NF/p}{m/m_o}$	m/m_o	$\frac{NF/p}{m/m_o}$
44	139	32	138
42	138	30	138
40	138	28	139

38	137	26	140
36	137	24	141
34	137	22	143

"The value of m/m_o corresponding to $\Phi = 4\theta$ is given by

$$m_o/m = \tan^2 \tfrac{1}{2}\Phi = \tan^2 2\theta = 0.0272$$

$$M/m_o = 36.7$$

Considerations of the Dimensions of the Apparatus.

"In designing physical instruments of precision, it is of importance to study the absolute scale of dimensions likely to yield the best results. Now, pressures being equal, the shorter the path of the beam of positive rays between the cathode and the photographic plate, the less likely it is to lose intensity and sharp outline through collisions. Also the smaller the area of the plate affected by a beam of given intensity, the easier will be its detection and the more accurate its measurement, for we are very far at present from the limits of accuracy of the measurement of position on the plate determined by the fineness of the grain of the emulsion. Hence, both these considerations point to an instrument of the smallest practical dimensions.

"The electric field offers no restrictions to such a development, for, once having decided the value of the deflexion θ_o and the potential at our disposal to produce it, the only quantity fixed is the ratio of the lengths of the plates to their distance apart. Their absolute dimensions are only limited by considerations of convenience of construction.

"The magnetic field, on the other hand, unfortunately dictates an inferior practical limit to the size of the instrument in an unequivocal manner. We have from the original exact equation for the motion of the charged particle in the magnetic field of intensity H,

$$HL/\delta = mv/e = (2\ m/e\ V)^{\frac{1}{2}}$$

where V is the potential through which the particle has fallen in the discharge tube. If we express V in volts and m on the ordinary chemical scale (O = 16) we get approximately $HL/\delta = 144\ (mV)^{\frac{1}{2}}$.

"Now H cannot very well be greater than 17,000 gauss for large pole-pieces. Actually the highest value used so far in this work is 15,000 gauss. Taking the values of the existing apparatus δ = 1/3 radian and H = 15,000, and allowing V to range from 20,000 to 50,000 volts, we find that while for the hydrogen atoms, (m = 1) the length of the field required ranges from 0.45 to 1.0 cms., for mercury (m = 200) it must range from 6.4 to 14.1 cms. (The actual length is 8 cms.)

"We see, therefore, that while it is possible to design a mass-spectrograph of precision on a small scale to investigate elements of lightness of hydrogen or helium, an apparatus capable of resolving the isotopes of the heavy elements must, of necessity, be on a considerable scale. Increase in the scale of the apparatus brings the necessity for extremely low pressure and other technical difficulties in its train, so that it appears probable that really great increase in resolving power, as in the case of X-rays, will have to come ultimately from an increase in the intensity of the beam of rays, enabling extremely narrow slits to be employed."[1]

[1] F.W.Aston & R.H.Fowler Phil. Mag. V43 514-516 (1922)

Discussion of the Parts of a Mass-Spectrograph

The Discharge Tube

Fig. 4 is a rough diagram of the arrangement of the mass-spectrograph when used for analysing positive rays generated by the ordinary discharge tube method. The discharge tube B is an ordinary X-ray bulb 20 cm. in diameter. The anode A is of aluminum wire 3 mm. thick surrounded concentrically by an insulated aluminum tube 7 mm. wide to protect the glass walls, as in the Lodge valve.

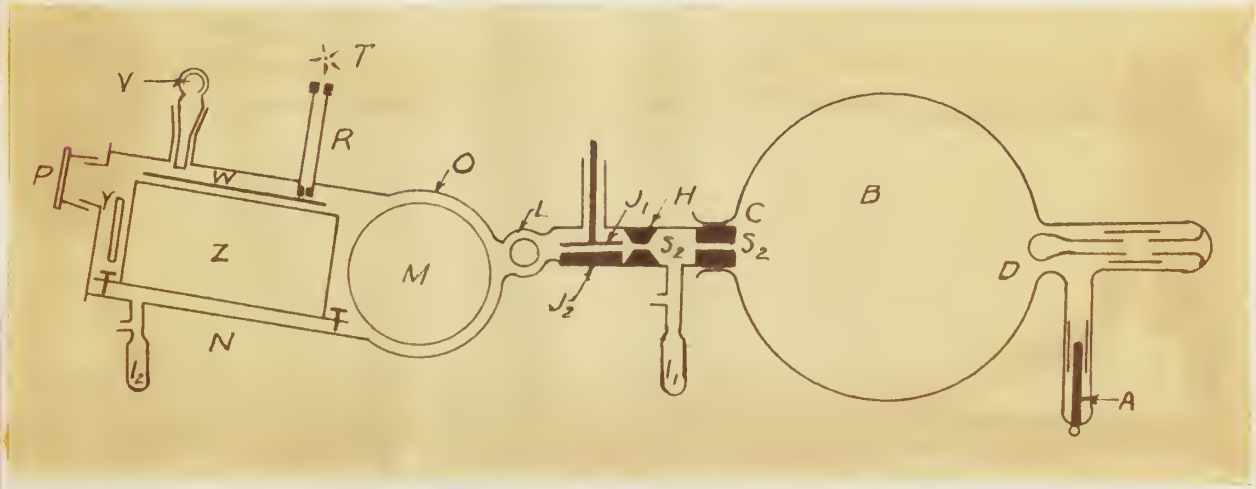


Fig. 4 Mass-Spectrograph. (after Aston)

The aluminum cathode C, 2.5 cm. wide, is concave, about 8 cm. radius of curvature, and is placed just in the neck of the bulb--this shape and position having been adopted after a short preliminary research. In order to protect the opposite end of the bulb, which would be immediately melted by

[1] F.W. Aston "Isotopes" p. 49-55

the very concentrated beam of cathode rays, a silica bulb D about 12 mm. diameter is mounted as indicated. The use of silica as an anticathode has the great advantage of cutting down the production of undesirable X-rays to a minimum. The cathode is earthed.

The discharge is maintained by means of a large induction-coil actuated by a mercury coal-gas break; about 100 to 150 watts are passed through the primary, and the bulb is arranged to take from 0.5 to 1 milliampere at potentials ranging from 20,000 to 50,000 volts. Owing to the particular shape and position of the electrodes, especially those of the anode, the bulb acts perfectly as its own rectifier.

The method of mounting the cathode will be readily seen from Fig. 5, which shows part of the apparatus in greater detail. The neck of the bulb is ground off short and cemented

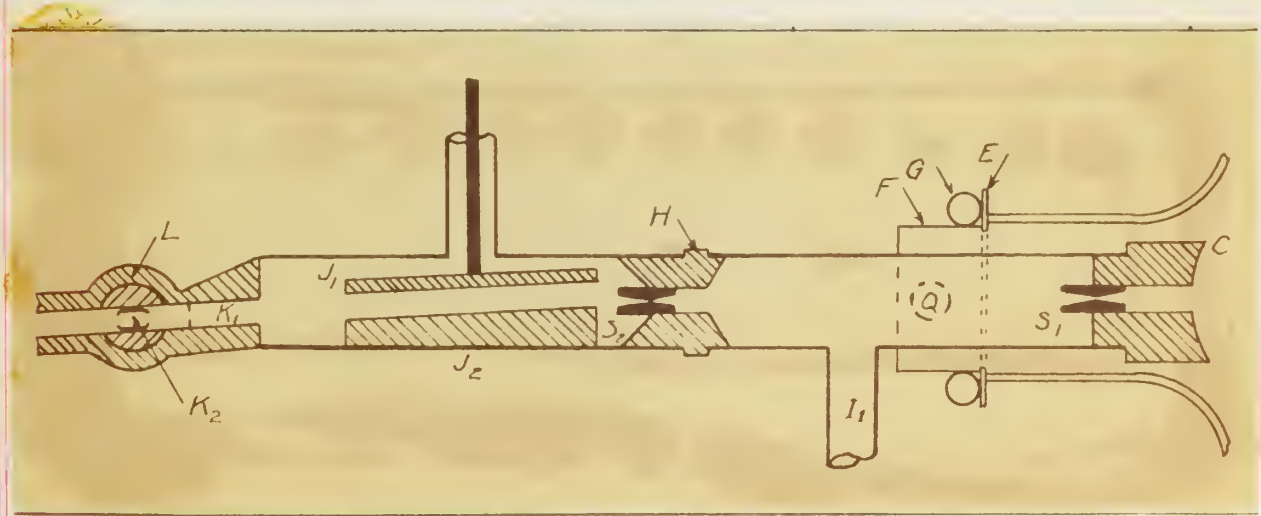


Fig. 5. Mounting of Cathode of Mass-Spectrograph. (after Aston)

with wax to the flat brass collar E, which forms the mouth of an annular space between a wide outer tube F and the inner tube carrying the cathode. The concentric position of the neck is assured by three small ears of brass not shown. The wax joint is kept cool by circulating water through the copper pipe shown in section at G.

The gas to be analysed is admitted from the fine leak into the annular space and so to the discharge by means of the side tube attached to F shown in dotted section at Q. Exhaustion is performed by a Gaede mercury-pump through a similar tube on the opposite side. The reason for this arrangement is that the space behind the cathode is the only part of the discharge bulb in which the gas is not raised to an extremely high potential. If the inlet or outlet is anywhere in front of the cathode, failing special guards, the discharge is certain to strike the pump or the gas reservoir. Such special guards have been made in the past by means of dummy cathodes in the bore of the tubes, but, notwithstanding the fact that the gas can only reach the bulb by diffusion, the present arrangement is far more satisfactory and has the additional advantage of enabling the bulb to be dismounted by breaking one joint only.

The Slit System

The very fine slits used in this apparatus were made with comparative ease as follows:--A cylinder of pure aluminum about 10 mm. long by 5 mm. wide is carefully bored with a hole 1 mm. diameter. The resulting thick-walled tube is then cleaned and crushed with a hammer on an anvil until the circular hole becomes a slit about.3 mm. wide. Continuation of this treatment would result in a slit as fine as required giving the maximum resistance to the passage of gas, but its great depth would make the lining up of a pair a matter of extreme difficulty. The crushed tube is therefore now placed between two V-shaped pieces of steel and further crushed between two points of the V's at about its middle point until the required fineness is attained. Practice shows that the best way of doing this is to crush until the walls just touch, and then to open the slit to the required width by judicious tapping at right angles to that previously employed. With a little care it is possible to make slits with beautifully parallel sides to almost any degree of fineness, .01 mm. being easily attainable. At this stage the irregularly shaped piece of aluminum is not suited to accurate gas-tight fitting; it is therefore filled with hard paraffin to protect it from small particles of metal, etc., which if entering cannot be dislodged owing to its shape, and turned up taper to fit the standard mountings. After turning, the paraffin is

easily removed by heat and solvents. The centre of the cathode is pierced with a 3 mm. hole, the back of which is coned out to fit one of the standard slits S_1. The back of the cathode is turned a gas-tight fit in the brass tube 2 cm. diameter carrying it, the other end of which bears the brass plug H which is also coned and fitted with the second slit S_2. The two slits, which are roughly .05 mm. wide by 2 mm. long, can be accurately adjusted parallel by means of their diffraction patterns. The piece between the slits, which are about 10 cm. apart, is kept exhausted to the highest degree by the charcoal tube I_1. By this arrangement it will be seen that not only is loss of rays by collision and neutralization reduced to a minimum, but any serious leak of gas from the bulb to the camera is eliminated altogether.

The Electric Field

The spreading of the heterogeneous ribbon of rays formed by the slits into an electric spectrum takes place between two parallel flat brass surfaces, J_1, J_2, 5 cm. long, held 2.8 mm. apart by glass distance-pieces, the whole system being wedged immovably in the brass containing-tube in the position shown. The lower surface is cut from a solid cylinder fitting the tube and connected to it and earth. The upper surface is a thick brass plate, which can be raised to the desired potential, 200--500 volts, by means of a set of small storage-cells. In order to have the plates as near together as possible, they are sloped at 1 in 20--i.e. half the angle of slope of the mean ray of the part of the spectrum which is to be selected by the diaphragms. Of these there are two: One, K_1, an oblong aperture in a clean brass plate, is fixed just in front of the second movable one, K_2, which is mounted in the bore of a carefully ground stopcock L. The function of the first diaphragm is to prevent any possibility of charged rays striking the greasy surface of the plug of the stopcock when the latter is in any working position. The variable diaphragm is in effect two square apertures sliding past each other as the plug of the stopcock is turned, the fact that they are not in the same plane being irrelevant. When the stopcock is fully open as sketched in Fig. 5, the angle of rays passing is a maximum, and it may be stopped down to any desired

extent by rotation of the plug, becoming zero before any greasy surface is exposed to the rays. Incidentally the stopcock serves another and very convenient use, which is to cut off the camera from the discharge tube, so that the latter need not be filled with air each time the former is opened to change the plate.

The Magnetic Field

After leaving the diaphragms the rays pass between the pole-pieces M of a large Du Bois magnet of 2500 turns. The faces of these are circular, 8 cms. diameter, and held 3 mm, apart by brass distance-pieces. The cylindrical pole-pieces themselves are soldered into a brass tube O, which forms part of the camera N. When the latter is built into position, the pole-pieces are drawn by screwed bolts into the arms of the magnet, and so form a structure of great weight and rigidity and provide an admirable foundation for the whole apparatus. Current for the magnet is provided by a special set of large accumulators. With a potential of 300 volts on the electric plates the hydrogen lines are brought on to the scale at about 0.2 ampere, and an increase to 5 amperes, which gives practical saturation, only just brings the singly charged mercury lines into view. The discharge is protected from the stray field of the magnet by the usual soft iron plates, not shown.

The Camera

The main body of the camera N is made of stout brass tube 6.4 cm. diameter, shaped to fit on to the transverse tube O containing the pole-pieces. The construction of the plate-

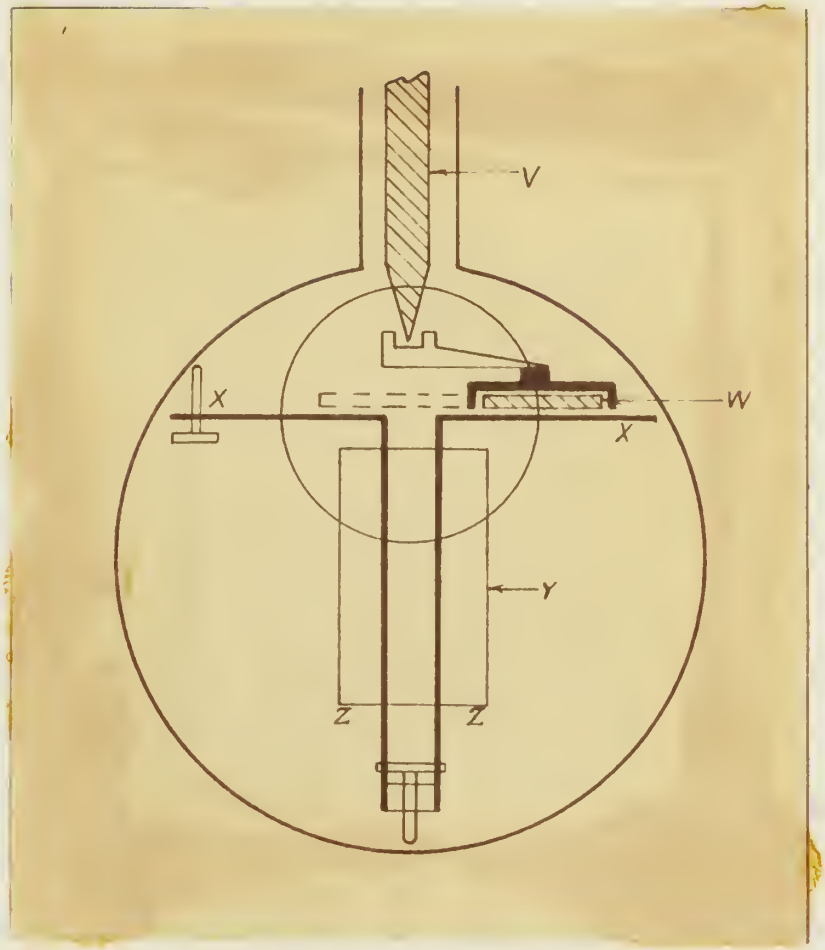


Fig. 6

The Plateholder of the Camera

holder is indicated by the side view in Fig. 4 and an end-on view in Fig. 6. The rays after being magnetically deflected pass between two vertical earthed brass plates Z, Z about 3 mm.

apart, and finally reach the photographic plate through a narrow slot 2 mm. wide, 11.8 cm. long, cut in the horizontal plate X, X. The three brass plates forming a T-shaped girder are adjusted and locked in position by a set of three levelling-screws at each end; the right-hand upper one is omitted in Fig. 6. The plates Z, Z serve to protect the rays completely from any stray electric field, even that caused by the photographic plate itself becoming charged until within a few millimetres of their point of impact.

The photographic plate, W, which is a 2 cm. strip cut lengthwise from a 5 by 4 plate, is supported at its ends on two narrow transverse rails which raise it just clear of the plate X, X. Normally it lies to the right of the slot as indicated, and to make an exposure it is moved parallel to itself over the slot by means of a sort of double lazy-tongs carrying wire claws which bracket the ends of the plate as shown. This mechanism, which is not shown in detail is operated by means of a torque rod V working through a ground glass joint. Y is a small willemite screen.

The adjustment of the plate-holder so that the sensitized surface should be at the best focal plane was done by taking a series of exposures of the bright hydrogen lines with different magnetic fields on a large plate placed in the empty camera at a small inclination to the vertical. On developing this, the actual track of the rays could be seen and the locus of points of maximum concentration determined. The final

adjustment was made by trial and error and was exceedingly tedious, as air had to be admitted and a new plate inserted after each tentative small alteration of the levelling-screws.

Experimental Procedure

The plate having been dried in a high vacuum overnight, the whole apparatus is exhausted as completely as possible by the pump with the stopcock L open. I_1, and I_2, are then cut off from the pump by stopcocks and immersed in liqued air for an hour or so. The electric field, which may range from 200 to 500 volts, is then applied and a small current passed through the magnet sufficient to bring the bright hydrogen molecule spot on to the willemite screen Y, where it can be inspected through the plate-glass back of the cap P. In the meantime the leak, pump, and coil, have all been started to get the bulb into the desired state.

When this has become steady, J_1 is earthed to prevent any rays reaching the camera when the plate is moved over the slot to its first position, which is judged by inspection through P with a non-actinc lamp. The magnet current having been set to the particular value desired and the diaphragm adjusted, the coil is momentarily interrupted while J_1 is raised to the desired potential, after which the exposure starts. During this, preferably both at the beginning and the end, light from a lamp T is admitted for a few seconds down the tube R, (Fig. 4) the ends of which are pierced with two tiny circular holes. The lower hole is very close to the plate, so that a circular dot or fiducial spot is formed from which the measurements of the lines may be made.

The exposures may range from 20 seconds in the case of hydrogen lines to 30 minutes or more, 15 minutes being usually enough. As soon as it is complete the above procedure is repeated, and the plate moved into the second position. In this way as many as six spectra can be taken on one plate, after which L is shut, I_2 warmed up, and air admitted to the camera. The cap, P, which is on a ground joint, can now be removed, and the exposed plate seized and taken out with a special pair of forceps. A fresh plate is now immediately put in, P replaced and the camera again exhausted, in which state it is left till the next operation.

Methods of Measuring Masses from Mass-Spectra

It can be shown,[1] by complicated mathematics[2] that the mass scale is approximately linear near $\Phi = 4\,\Theta$.

Φ = the angle through which the beam of rays is bent in passing through the magnetic field.

Θ - the angle through which the beam of rays is bent in passing through the electric field.

If the geometrical constants of the machine remain fixed, that is, so long as the apparatus is rigid: "Then let D_1 and D_2 be the distances from the fiducial spot of any two points on the plate and m_1 and m_2 the corresponding masses for given values of D_1 and D_2, the ratio m_1/m_2 will be the same in every photograph."[3]

[1] F.W. Aston, "Isotopes" p. 56
[3] F.W. Aston, "Isotopes" p. 57
[2] p. 11 of this thesis

In deducing the effective mass of a particle from its position on the plate, a purely empirical process must be used and a mathematical study, such as the one from which the above data was taken, is of no practical use and is interesting only because it explains the results obtained.

"The procedure was somewhat as follows: A series of spectra were taken with, say a mixture of CO_2 and CH_4 in the discharge tube. Previous experience with the parabola method of analysis led to the expectation that lines at 6-C^{++}, 8-O^{++}, 12-C, 16-O, 28-CO, 32-O_2, 44-CO_2, would certainly be present, there would also be a series of hydrocarbon lines between 12 and 16, CH, CH_2, CH_3, which could be regarded as known. A spectrum was selected containing as many as possible of these known lines and their masses m_1, m_2, m_3,--were plotted against the distances of the lines from the fixed fiducial spot and a curve drawn through the points so obtained. This is our first calibration curve--of necessity inaccurate owing to the gaps between the points. A second spectrum was now taken in which the same lines appeared in a different place, for by altering the magnetic field we can place them wherever we please, and the new set of distances from the fiducial spot measured. These distances were now transformed into masses (no longer integral) m'_1, m'_2, m'_3,--by means of the curve previously drawn. Supposing the curve to be accurate and the ratio law to hold $\frac{m'_1}{m_1} = \frac{m'_2}{m_2} = \frac{m'_3}{m_3} = r$ where r is clearly a

measure of the change in m_o in the mathematical discussion above."[1]

"Where m_o is a constant and can be interpreted as that mass which under the conditions of the experiment is bent through a right angle in the magnetic field."[2]

The known masses multiplied by the mean value of 'r' give a new set of points on the original calibration curve. By suitably altering the magnetic field all the gaps in the curve can be filled in and a curve of any desired degree of accuracy obtained.

From this curve the identification of one line is possible and so all other lines on the plate can be related to it. Since each plate generally contains many known lines the accuracy of calculation is checked at each known line.

Since there is a linear relation at $\mathfrak{D} = 4\,\Theta$ the curve is very close to straight for a considerable portion of its length. The masses can be deduced from this linear relation if desired.[4] "A linear relation was assumed and a table of corrections made by means of reference lines, and these corrections when subtracted from the observed displacements gave an exactly linear relation with mass. A correction-curve (apparently parabolic) was drawn, from which the appropriate correction for any displacement could be written down and

[1] F.W. Aston, "Isotopes" p. 57-58
[2] F.W. Aston, "Isotopes" p. 56
[3] F.W. Aston, "Isotopes" p. 58
[4] F.W. Aston, "Isotopes" p. 58

the mass corresponding to this displacement obtained by simple proportion."

The foregoing examples are straight forward and have the added advantage of not requiring a knowledge of the numerical values of the fields used, the only requirement being, that the fields be kept constant. The method of "Coincidence" requires no knowledge, either theoretical or empirical, of the relation between mass and displacement.

This method is independent of a calibration curve and serves as a check on the previous methods. It has several disadvantages but in spite of these, the principle underlying this method gives the most accurate mass ratio measurements. If we wish to measure the ratio of m'/m_3 where m' is the unknown mass and m the known mass, we would first make a mass spectrum with fields X and H such that m would cause a line on the plate in a certain position. Now the fields are altered to X' and H' until the line caused by m' is in the identical position of the line caused by m.

The magnetic field H is hard to reproduce and cannot be measured and the electric field X which can be measured very easily and accurately, is the one that is changed while H is kept constant.

If Θ and Φ[1] be the angles taken algebraically through which the selected beam of rays is bent by passing through

[1] See page 11 of this thesis.

the fields of strength X and H, then:

$$\frac{1}{2} v^2 = 1X\ e/m \quad (1), \text{ and } \frac{1}{2} V = LH\ e/m \quad (2)$$

It follows from (1) and (2) that $m'/m = X/X' (H'/H)^2$

When the investigation of the heavy elements was begun, the problem of nomenclature for these many isotopes became serious. The most popular plan today is to give the chemical symbol for the element an exponent corresponding to its mass thus: Ne^{22}, Rb^{87}, and so on.

"This index is called the "mass-number" of the atom. It may be defined in two ways. Theoretically, it is the number of protons in the atom, practically it is the nearest whole number to its weight expressed on the ordinary chemical scale."[1]

[1] F.W. Aston, "Isotopes" p. 64

The Dempster Method of Analyzing Positive Rays

Another arrangement which has been used widely was originally employed by Classen to measure the e/m of the electron and first adapted to positive rays by Dempster.[1] "The charged particles from some source fall through a definite potential difference. A narrow bundle is separated out by a slit and is bent into a semi-circle by a strong magnetic field; the rays then pass through a second slit and fall on a metal plate connected to an electrometer. The potential difference P, magnetic field H, and radius of curvature r, determine the ratio of the charge to the mass of the particle by the formula."[2]

$$e/m = 2P/H^2r^2$$

The ions are emitted from hot filaments coated with suitable materials or are drawn from a low-voltage discharge in gases. This method has found its widest use in the study of products of ionization and ionizing potentials in gases.

[1] Dempster, Phys. Rev. Vol. 11, p. 316 (1918)
[2] F.W. Aston "Isotopes" p. 33

A High Intensity Mass-Spectrograph

Bleakney[1] has devised a mass-spectrograph of high intensity and low resolving power by allowing the ions to fall from a source through a devinite potential difference thereby gaining energy after which they are passed through a type of velocity filter. This filter makes use of an electric and magnetic field simultaneously, the direction of the fields and the direction of the projection of the ion beam being mutually perpendicular. The magnetic field in most instruments is obtained from the pole pieces of a strong electromagnet. These poles must be close together to give a strong, uniform field and hence the slits cannot be very long. In Bleakney's instrument the magnetic field is produced by a long solenoid within which the whole apparatus is placed. Hence, slits several centimeters long can be used without the loss of resolving power. This instrument is operated under a pressure of the order of 10^{-6} mm. At pressures as low as this only a small fraction of the ions formed ever collide with other molecules before reaching the final collector. Because of this low collision rate, this instrument finds great use in the study of the so-called primary ionization in gases. Since the instrument has a remarkable sensitivity it lends itself readily to the study of very rare isotopes of light elements. In favorable cases isotopes existing to the extent of one part

[1] Walker Bleakney, Phys. Rev. V. 34 157 (1929)
V. 40 496 (1932)

per million can be detected. The chief disadvantage of this type of mass-spectrograph is the low resolving power, limited by the size of the instrument and the magnetic field.

The Bainbridge High-Precision Instrument

A mass-spectrograph of high-precision for measuring the masses of isotopes, has been designed by Bainbridge. Bainbridge combined a velocity filter, similar to the one used by Bleakney and described on page 36-37, with a momentum filter. The momentum filter produces a beam of ions which are homogeneous in momentum by projecting a heterogeneous beam through and at right angles to a uniform magnetic field. This apparatus has some very good features. First, the ions fall perpendicularly upon the photographic plate and produce a trace which is symmetrical in density about the center of the line. This allows accurate measurements to be made of line separations even though the lines differ in intensity. Second, the mass is a linear function of the distance along the plate. Under favorable conditions the probable error in measurement is of the order of 1 part in 10^5.

Possibly one disadvantage of this set up is that, because of the use of the velocity filter, the ions falling on the plate do not come from the same region of the discharge; consequently, relative abundance measurements are hard to obtain with any accuracy.

A Mass-Spectrograph Without the Use of Magnetic Field

Smythe[1] has worked out the theory of a velocity filter using alternating electric fields. The incoming particle is caused to pass between the plates of two sets of two condensers each. An alternating electric field is applied to these condensers and only those particles get through whose velocity and phase satisfy certain relations. Hence the device acts as a velocity filter. This arrangement is analogous to the toothed wheel method of Fizeau[2] for measuring the velocity of light.

By using this velocity filter in conjunction with an energy filter Smythe and Mattauch[3] have built a mass-spectrograph with no magnetic fields. The energy filter used involved application of an electric field perpendicular to the direction of motion of the ions.

This arrangement has many inherent advantages in the way of resolving power and ability to compare accurately ions of widely different masses. It has been little used, however, because it is rather a delicate piece of apparatus to construct.

[1] W.R. Smythe Phys. Rev. V. 28 1275 (1926)

[2] V. Edwin Edser Light for Students 222-226

[3] W.R. Smythe and J. Mattauch, Phys. Rev. V 40 429 (1932)

Other Types

Bartky and Dempster[1] discussed the theory of the simultaneous application of an energy filter (the electric field perpendicular to the direction of motion of the ions) and a momentum filter, (projection of a heterogeneous beam through and at right angles to a uniform magnetic field thus giving a beam of ions homogeneous in momentum). They advocated making the electric field equal to 1/R and perpendicular to the magnetic field. (R = radius of path of ions through the electric field.) Bondy and Popper[2] built an apparatus according to this plan and found it to work satisfactorily.

The "cyclotron" invented by Lawrence[3] for the production of very high energy ions might be used as a mass-spectrograph since it sorts out a particular e/m.

1 Bartky and Dempster Phys. Rev. V. 33 1019 (1929)
2 Bondy and Popper Ann. der Physik V. 17 28 (1933)
3 Lawrence and Livingston Phys. Rev. V. 40 19 (1932)

Practical Uses of the Mass-Spectrograph and Some of the Results Obtained In the Determination of Isotopes and Atomic Weights

In the study of the constitution of the elements there are two groups which must be considered. One group deals with those elements, which by reason of their volatility or properties of forming volatile compounds, can be treated by the ordinary discharge tube method. Whenever this is possible the mass-spectrograph is used. The other group, all metals, deals with those elements whose positive rays must be generated by special devices. In the first group are:
Oxygen 16.00[1], Carbon 12.00, Neon 20.20, Chlorine 35.46, Argon 39.99 by Ramsey, 39.91 by Ledus, Nitrogen 14.01, Hydrogen 1.008, Helium 4.00, Triatomic Hydrogen H_3, Krypton 82.92, Xenon 130.2, Mercury 200.6, Boron 10.82, Flourine 19.00, Silicon 28.06, Bromine 79.92, Sulphur 32.06, Phosphorus 31.04, Arsenic 74.96, Selenium 79.2, Iodine 126.92, Antimony 121.77, Tin 118.70, Nickel 58.69, Iron 55.84, and Aluminum 26.96.

"Research on isotopes,[2] properly speaking, began in 1919, with Aston's development of positive ray analysis into the so-called mass-spectroscopy. Using this new method, Aston was first able to prove, with greater accuracy, that the rare gas, neon, does actually consist of two isotopes with the exactly

[1] Numbers refer to atomic weights.
[2] Isos Topos in Greek means "the same place", name suggested by the fact that isotopes occupy same place in periodic system.

integral atomic weights of 35.0 and 37.0. It follows that from the mixture weight (35.46) the ratio of the lighter to the heavier gas is about three to one, as can be recognized from the intensity of the lines in the mass-spectra."[1]

Due to the limited scope of this thesis, the manner of determining isotopes will be discussed for only one simple case, that of neon. The following discussion is taken directly from Aston's original papers and his book entitled "Isotopes."

"On a mass-spectrum all measurements are relative, and so any known element could be taken as a standard. Oxygen is naturally selected. Its molecule, singly-charged atom, and doubly-charged atom give reference lines at 32, 16, and 8 respectively. The extremely exact integral relation between the atomic weights of oxygen and carbon is itself strong evidence that both are "simple" elements, and so far no evidence appears to have arisen to throw any doubt on this point. Direct comparison of the C line (12) and the CO line (28) with the above standards shows that the whole number relation and additive law hold to the limit of accuracy, i.e. one part in a thousand; and this provides standards C^{++} (6) C (12), CO (28), and CO_2 (44).

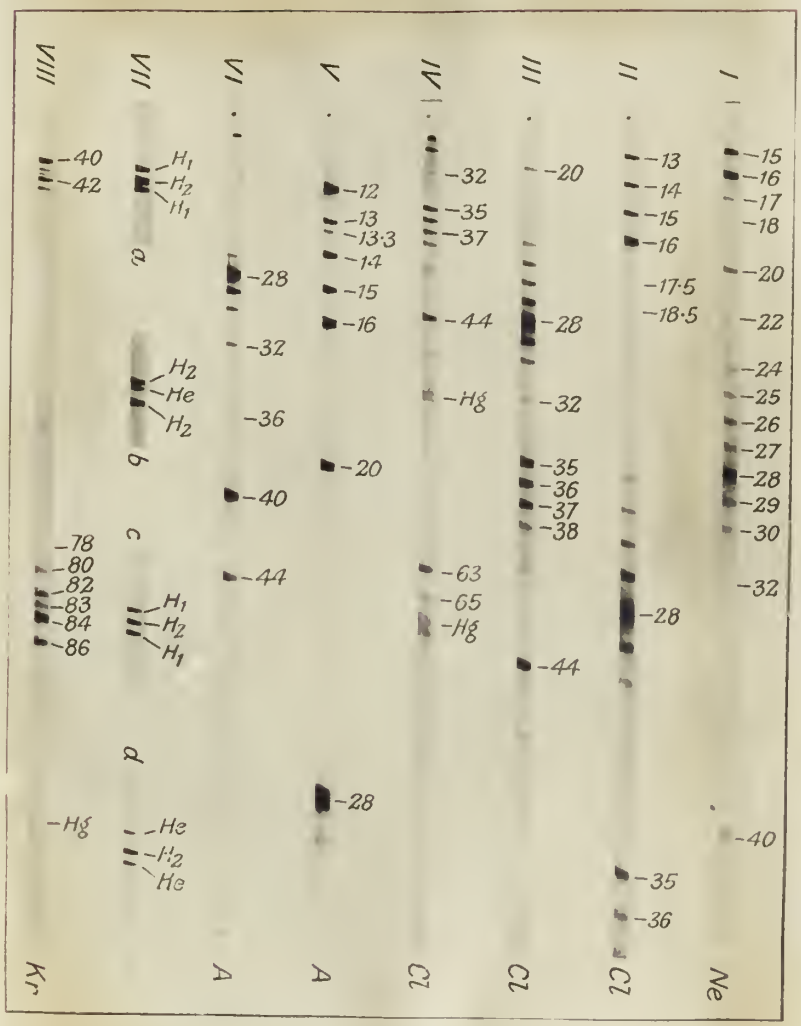
Many of these lines will be recognized on the spectra reproduced on Plate III, page 44. The compounds of carbon and hydrogen provide two valuable and easily distinguishable groups of reference lines. The first: which may be

[1] Arthur Haas, Atomic Theory 91

called the C_1 group, contains five:--12-C, 13-C, 13-CH, 14-CH_2, 15-CH_3, 16-CH_4 (or O). It is very well shown on Spectrum V' Plate III. When water vapour is present, and particularly when a fresh discharge-tube is used for the first time, it is followed by 17-OH, 18-OH_2, and sometimes by 19, presumably OH_3, but always very faint. The second hydrocarbon or C_2 group contains seven lines:--24, 25, 26, 27, 28, 29, 30, which include the very strong and particularly valuable reference line 28 or CO or C_2H_4. This group is well illustrated in Spectra I and II, Plate III. All the above lines may be expected on spectra obtained by the ordinary discharge-tube method; for an addition of CO or CO_2 is usually made to the gases of vapours under consideration and assists the smooth running of the discharge. The hydrocarbons are derived from the wax and grease in the joints of the apparatus.

"As soon as the instrument was found to work satisfactorily and enough mass-spectra containing reference lines had been obtained, neon was introduced into the discharge tube. The best results were obtained with a mixture of carbon monoxide and neon, containing about 20 per cent. of the latter gas.

"The first order two and second order two lines due to neon were all four available and well placed for measurement on the mass-spectra obtained. The following figures are taken from the original paper; (Aston, Phil. Mag. V. 39, 454 (1920) they are the results of the measurements made on two different plates, using six different spectra.



Mass Spectra.

Plate III Mass Spectra (After Aston)

Plate 1.

First Order		Second Order	
20.00	22.00	9.98	11.00
19.95	22.01	10.02	10.99
19.97 (5)	22.00 (5)	10.00	10.99(5)

Plate 2.

20.00	21.90	10.01	11.06
19.98	22.10	9.98	10.98
20.00	22.03	9.98	11.01
19.90	21.98	—·—	—·—
19.97	22.00 (5)	9.99	11.01

"The method of measuring the position of the lines then in use, combined with a photographic halation effect, tended to decrease the masses given by very bright lines. This is enough to account for the reading of the intense 20 line giving a mass a little too low. The above figures therefore can be accepted as conclusive evidence that neon is a mixture of two isotopes of atomic weights 20.00 and 22.00 (O = 16) respectively, to an accuracy of about one-tenth per cent. (Aston, Nature, Nov. 27, 1919; Phil. Mag. V 39, 454, 1920)

"The two first order lines of neon are shown in Spectrum I, Plate III, but, of course, their relative intensities must not be judged from such a half-tone reproduction. On the original negatives the intensities are in good agreement with the expected ratio 9 to 1 which is necessary to yield the accepted atomic weight 20.20. On some of the clearest spectra

obtained with neon present there is a distinct indication of a line corresponding to a mass 21. This is an exceedingly faint line and, at first, was thought to indicate the presence of a third isotope. It is now considered more probably due to an abnormal hydride."[1]

The determination of the masses of hydrogen and helium, which are far removed from the ordinary reference lines, is accomplished by the method of "Bracketing."[2]

The second group is composed of metallic elements whose positive rays cannot be obtained by the ordinary discharge-tube method, since, in general, they have very low-vapor pressures and are unable to form stable volatile compounds. This group of elements consists of Lithium 6.94[3], Sodium 23.00, Potassium 39.10, Rubidium 85.45, Caesium 132.81, Berylliam 9.02[4], Magnesium 24.32[5], Calcium 40.07, Zinc 65.38, Germanium 72.38, Copper 63.57[6], Strontium 87.63[7], Barium 137.37[7], Cobalt 58.97, Scandium 45.10, Manganese 54.93, Gallium 69.72, Vanadium 50.96, Chromium 52.01, Titanium 48.1, Silver 107.88, Yttrium 88.9, Indium 114.8, and some of the rare earth elements.[8] (Lanthanum 138.91, Praseodymium 140.92, Cerium 140.25, Neodymium 144.27, Erbium 167.7)

[1]Aston "Isotopes" p 65-67
[2]V. Aston "Phil. Mag." V. 39 621 (1921)
[3]Aston and Thomson "Nature" V. 106-828 (1921)
[4]G.P.Thomson "Phil. Mag." V. 42 857 (1921)
[5]Dempster "Science" Dec. 10, 1920
[6]Dempster "Nature" July 7, 1923
[7]Aston, "Nature" V. 112 449 (1932)
[8] V. Aston, "Nature" V 113 856 (1924)

A full description of the methods for overcoming the non-volatility of these technicalities, a very good account is given in Aston's "Isotopes" pages 84 to 108 or the original papers cited in the footnotes of this thesis. A very brief digest of these methods will, however, be given.

In analyzing the metals of the alkali group a "hot-anode" discharge tube[1] was devised. The hot anode is a strain of platinum foil welded to two platinum leads which are fused through the side of the glass tube. This anode was fitted into the tube by means of a ground glass joint. The anode was raised to the required temperature by current from a large storage cell connected through a rheostat. The platinum strip was bent into a "U" shape in which the salts could be placed by taking the tube apart at the ground joint. The anode was about 1 cm. away from the perforated cathode.

A modification of Thompson's Parabola Method was used but with very little success.

A modification of Dempster's original apparatus, in which the anode rays were derived from heated salts, to one in which the metals themselves are vaporized, this vapor being the ionized by bombardment with electrons, has proved successful.

Aston[2] developed an apparatus for accelerated anode rays[3]

[1]Aston, Phil. Mag. V. 42 436 (1921)
[2]Aston, Phil. Mag. V. 47 385 (1923)
[3]Aston, Phil. Mag. V. 49 p(1191) (1925)

which was capable of giving beams of high enough intensity and under sufficient control to be applied to the mass-spectrograph.

A graphite paste is mixed with the metallic salts and placed in a cavity in the end of the anode. The anode is so made that it can be withdrawn, filled with paste, and replaced with great accuracy. A Kenotron tube is used to maintain a constant current through the discharge tube.

Table of Elements and Isotopes.

Element.	Atomic Number.	Atomic Weight.	Minimum number of Isotopes.	Mass-numbers of Isotopes in order of Intensity.
H	1	1·008	1	1
He	2	4·00	1	4
Li	3	6·94	2	7, 6
Bo	4	9·02	1	9
B	5	10·82	2	11, 10
C	6	12·00	1	12
N	7	14·01	1	14
O	8	16·00	1	16
F	9	19·00	1	19
Ne	10	20·20	2	20, 22
Na	11	23·00	1	23
Mg	12	24·32	3	24, 25, 26
Al	13	26·96	1	27
Si	14	28·06	2	28, 29, (30)
P	15	31·02	1	31
S	16	32·06	1	32
Cl	17	35·46	2	35, 37
A	18	39·88	2	40, 36
K	19	39·10	2	39, 41
Ca	20	40·07	2	40, 41
Sc	21	45·1	1	45
Ti	22	48·1	1	48
V	23	51·0	1	51
Cr	24	52·0	1	52
Mn	25	54·93	1	55
Fe	26	55·84	2	56, 54
Co	27	58·97	1	59
Ni	28	58·68	2	58, 60
Cu	29	63·57	2	63, 65
Zn	30	65·38	4	64, 66, 68, 70
Ga	31	69·72	2	69, 71
Ge	32	72·38	3	74, 72, 70
As	33	74·96	1	75
Se	34	79·2	6	80, 78, 76, 82, 77, 74
Br	35	79·92	2	79, 81
Kr	36	82·92	6	84, 86, 82, 83, 80, 78
Rb	37	85·44	2	85, 87
Sr	38	87·63	2	88, 86
Y	39	88·9	1	89
Ag	47	107·88	2	107, 109
In	49	114·8	1	115
Sn	50	118·70	7 (8)	120, 118, 116, 124, 119, 117, 122, (121)
Sb	51	121·77	2	121, 123
I	53	126·92	1	127
X	54	130·2	7 (9)	129, 132, 131, 134, 136, 128, 130, (126), (124)
Cs	55	132·81	1	133
Ba	56	137·37	(1)	138
Hg	80	200·6	(6)	(197), 202, 198, 199, 200 204

(Numbers in brackets are provisional only.)

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Table I Table of Elements and Isotopes (After Aston)

Summary of the Types of Mass-Spectrographs

Inventor and Common Name	Manner in which particles of different mass are separated.
[1]Thomson's Positive Ray Apparatus	A beam of rays is passed through magnetic and electric fields which occur at the same place, both fields being in the same direction.
[2]Aston's Mass-Spectrograph	A very narrow beam of rays pass between two parallel plates charged electrically. The central portion of this electric spectrum is then passed through a magnetic field at right angles to the electric field.
[3]Dempster's Method of Positive Ray Analysis	A narrow bundle of positive rays is passed over a semi-circle in a strong magnetic field and allowed to fall on a metal plate connected to an electrometer.
[4]Bleakney's High Intensity Mass-Spectrograph	The ion beam is subjected to electric and magnetic fields simultaneously. The whole instrument is within a long solenoid which produces the magnetic field. Hence, very long slits can be used without the loss of resolving power. The direction of fields and ion beam are mutually perpendicular.
[5]Bainbridge's High Precision Instrument	This instrument is the same as Bleakney's with the addition of a uniform magnetic field. A beam of ions heterogeneous in momentum is projected through and at right angles to this field thus giving a beam homogeneous in momentum.

1 F.W. Aston, "Isotopes" 28-29

2 F.W. Aston, "Isotopes" 49 and following

3 Dempster, "Phys. Rev." V. 11 316 (1918)

4 Bleakney, "Phys. Rev." V. 34 157 (1924); V.40 496 (1932)

5 Bleakney, Am. Phys. Teach. V. 4, No. 1 17 (1936)

[6]A Mass-Spectrograph without Magnetic Fields.	An alternating current is applied to the plates of two sets of two condensers each. The beam passes between the plates and only those particles pass the velocity and phase of which satisfy the characteristics of the field.

[6] Smythe and Mattauch "Phys. Rev." V. 40 429 (1932)

Digest

In the introduction is set forth the objectives and scope of the thesis. Following this is a brief historical account of the work of Goldstein, Wein, and Thomson on positive rays. A diagram of the positive rays apparatus, positive rays parabolas, and an actual photograph of positive rays together with the accompanying explanation serve to interpret the method of determining the "charge--mass ratio" of particles investigated by this method.

Aston's work on mass-spectroscopy forms the body of this thesis. First, there is a brief account of the first mass-spectrograph and the principle on which it works. A copy of a photograph of the original mass-spectrograph follows this introduction into Aston's work. Second, there is the exact mathematical derivation of the theory of the mass-spectrograph taken from Aston and Fowler's original paper. The mathematica of the instrument is of no use in its operation and is interesting only because it explains and proves what is observed when the instrument is used. That is to say, that the mass-scale is nearly linear at the point where $\Phi = 4\,\Theta$. Φ and Θ being the angles through which the particle is bent in passing through the magnetic and electric fields respectively. Third, there is the discussion of the size of the apparatus which depends on the particle being investigated and theoretically ranges from a field length of 0.45 cma. for hydrogen to

one of 14.1 cms. for mercury. The actual length used was 8 cms. Fourth, is a discussion of the parts of Aston's mass-spectrograph:- the discharge tube, the cathode mounting, the slit system and the technical difficulties of making a suitable slit and how they were overcome, the electric field, the magnetic field, the camera and how it is made and used, and the experimental proceedure in the use of the instrument. Fifth, is a discussion of the manner of measuring masses from mass-spectra.

Next to the last section of the thesis is a description of several other types of mass-spectrographs that have been used but are not as important as Aston's.

First of these types is Dempster's method of analyzing positive rays. Second, a high intensity mass-spectrograph as devised by Bleakney and used to study very rare isotopes of light elements. Thirs, is Bainbridge's high precision instrument where errors in measurement of the order of 1 part in 100,000 are possible. Fourth, the mass-spectrograph with no magnetic fields. Here an alternating electric field is used to sort out particles and only those particles get through which satisfy the characteristics of the field. The chief advantage of this instrument is its high resolving power and ability to compare accurately ions of widely different masses.

The last part of the thesis deals with the methods of producing isotopes to be photographed, the results so far ob-

tained and the method of deriving atomic weights from the isotopes. The method of arriving at the atomic weight of one element, neon, is given as an example of the proceedure used in all cases. The last page of the thesis proper is a table of elements with their corresponding atomic weights and isotopes.

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Abbreviations used in Bibliography

"Am. Phys. Teach."	The American Physics Teacher.
"Ann. de Physique"	Annales de Physique.
"Ann. der Physik"	Annalen der Physik.
"Eng."	Engineering.
"Jour. Am. Chem. Soc."	Journal of the American Chemical Society.
"Jour. Chem. Soc."	Journal of the Chemical Society.
"Jour. Inst. Met."	Journal of the Institute of Metals.
"Phil. Mag."	Philosophical Magazine and Journal of Science.
"Phys. Rev."	Physics Review
"Proc. Camb. Phil. Soc."	Proceedings at the Cambridge Philosophical Society.
"Proc. Roy. Soc."	Proceedings at the Royal Society of London.